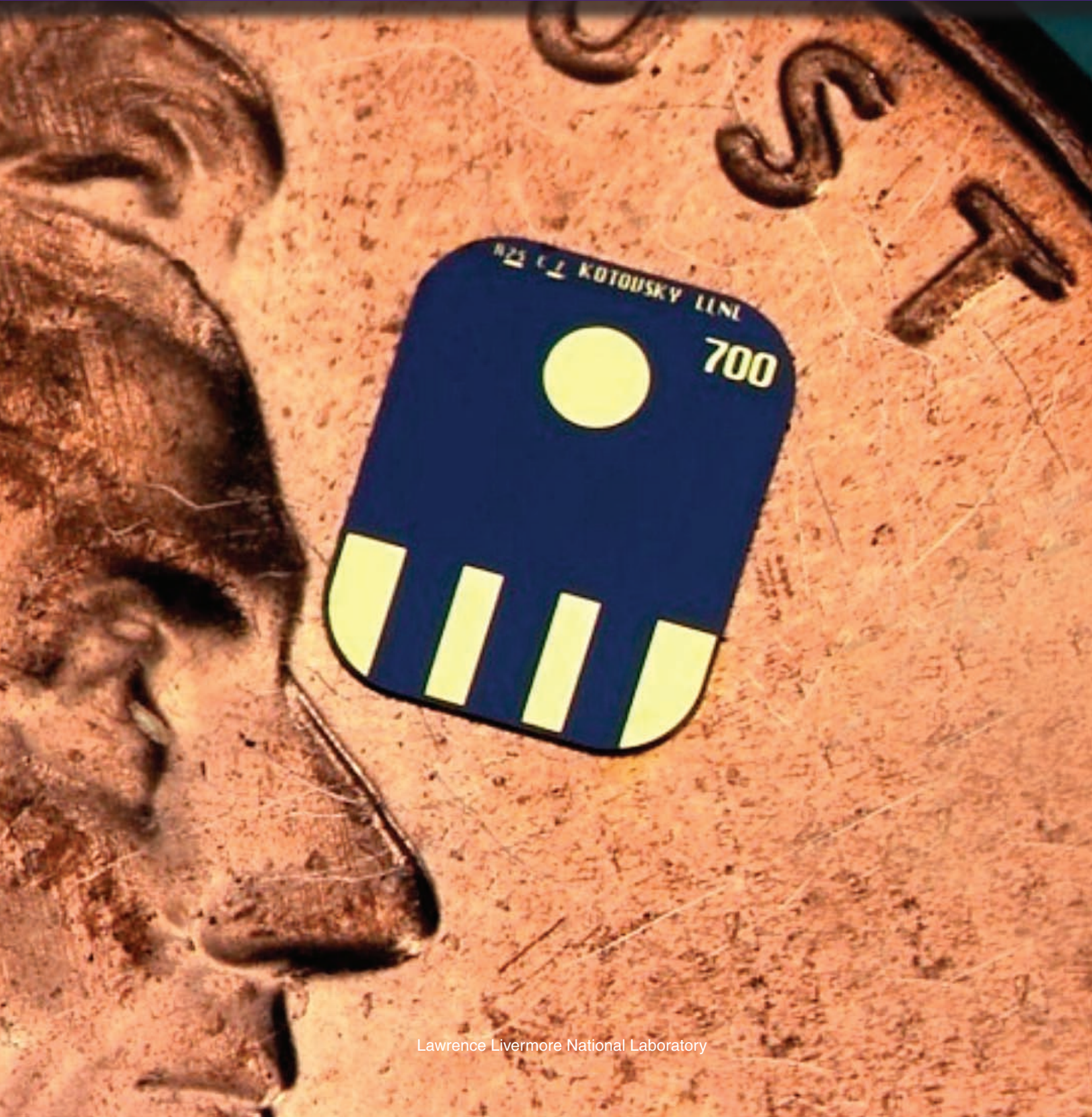


# Monitoring a Nuclear





# Weapon

## from the Inside

*Embedded sensors could help transform stockpile stewardship.*

**T**HE paramount national security mission of Lawrence Livermore is ensuring the safety and reliability of the nation's nuclear weapons stockpile. Development of new nuclear weapons systems stopped nearly two decades ago, and today, the nation's stockpile is maintained through a science-based stockpile stewardship program. However, as weapon components age, ensuring the reliability of the stockpile has become an increasingly complicated and costly challenge.

The Department of Energy's National Nuclear Security Administration (NNSA) is working to transform the U.S. nuclear weapons complex and the nation's stockpile by shrinking the size of both and finding more cost-effective ways to maintain the remaining weapons. In short, procedures developed during the Cold War to ensure that the stockpile meets all performance requirements must be replaced with a more efficient approach, made possible by using modern technologies.

"The nuclear weapons complex is at a crossroads—maintaining the status quo is not an option we can afford," says NNSA Administrator Thomas D'Agostino. "Delay and inaction will only increase the costs and elevate the risks associated with maintaining an aging stockpile." (See the box on p. 15.)

Livermore scientists and engineers are providing technical leadership to achieve this transformation. According to Livermore physicist Jim Trebes, "Weapons are hard to maintain; we want to do the job faster, better, and cheaper." One of the most needed improvements is a cost-effective method to collect data about the state of nuclear weapon components, in particular, to detect corrosion, cracks, and composition-changing properties without having to dismantle the weapons. Traditionally, a few randomly selected warheads and bombs are pulled from the field every year and transported to NNSA's Pantex Plant in Texas, where they are disassembled for close inspection. While

Tiny sensors similar to the one shown here could be embedded in the nation's nuclear weapons to detect anomalies such as cracks or corrosion in weapon components.

most are reassembled and returned to the stockpile, at least one warhead of each type is destroyed in the process. Some parts, for example, are cut open for inspection, and others are stressed to the failure point.

A promising Livermore effort is developing tiny, rugged sensors that could be embedded in every nuclear weapon. Embedded sensors, compatible with warhead materials, could provide information currently obtained from disassembly. Such devices could make possible for the first time “persistent surveillance”—continuous monitoring of the state of health for every weapon and practically instantaneous detection of anomalies.

Eliminating the costly and sometimes destructive testing of warheads is particularly important to comply with the Moscow Treaty on Strategic Offensive Reductions, which was signed in 2002. Under the terms of this treaty, the U.S. is reducing its total number of active nuclear

weapons to between 1,700 and 2,200 warheads and bombs. As the number of U.S. weapons shrinks, fewer weapons are available for disassembly to provide statistical assurance about the stockpile’s health.

Sensors would most likely be embedded in existing weapons during a life-extension program—a rebuilding effort that significantly increases a warhead’s lifespan. Sensors could also be added to so-called shelf units stored at NNSA’s Y-12 Plant in Tennessee and at Pantex, where individual components are monitored closely for signs of aging and unexpected physical and chemical changes. In addition, if replacement warheads were developed, sensors could be integrated into the weapon assembly.

Once in place, an array of different sensors could signal the presence of unwanted gases, record stresses incurred as a warhead is moved, and detect microscopic cracks and voids. Trebes, who is helping guide Livermore sensor designs, notes that an embedded sensor network might also reveal “unknown unknowns,” issues not previously encountered.

“If we could assess every weapon in real time, we would immediately know which warheads need to be pulled apart, and that would drive down costs,” says chemist Lou Terminello, who leads the Laboratory’s

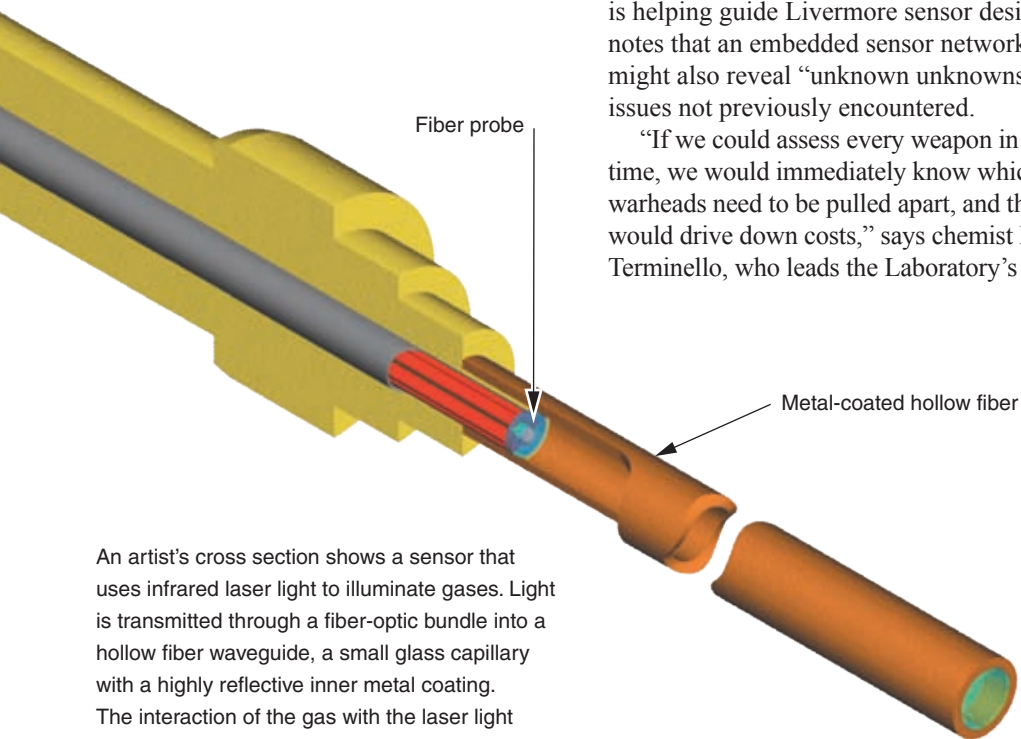
materials program. Bruce Goodwin, principal associate director for Weapons and Complex Integration, adds, “Embedded sensors have the potential for a huge payoff in costs and manpower. They will give us stronger confidence in the stockpile. Instead of sending all 30 kids in a classroom to get a physical exam, one kid raises his hand and says, ‘I’m sick.’”

### Diverse Sensor Development Team

The sensor development program includes about 15 engineers, chemists, physicists, and computational scientists. The effort taps Laboratory expertise in microfabrication, forensic science, nuclear chemistry, photonics, medical technology, homeland security, and computer modeling. The developers were inspired, in part, by the electronic sensors that monitor dozens of parts and systems in cars. Experimenters at the Laboratory’s High Explosives Application Facility have also successfully used microscopic sensors for several years, embedding them in high-explosive formulations to track aging effects.

Livermore’s Laboratory Directed Research and Development Program funds much of this research through the Transformational Materials Initiative, which is focused on creating materials, processes, and diagnostics to support NNSA’s complex transformation. New technologies can also be applied to other fields, including energy, nonproliferation, global security, and health care. According to Livermore physicist Robert Maxwell, who leads this research effort, “The initiative has allowed us to pursue advanced sensor ideas.” Designs that mature beyond the proof-of-principle stage are then funded by NNSA.

Collaborating institutions include Georgia Institute of Technology, University of South Carolina, the United Kingdom’s Atomic Weapons Establishment (AWE), and other NNSA sites. A joint working group, with representatives from throughout



An artist's cross section shows a sensor that uses infrared laser light to illuminate gases. Light is transmitted through a fiber-optic bundle into a hollow fiber waveguide, a small glass capillary with a highly reflective inner metal coating. The interaction of the gas with the laser light identifies the gas.



the NNSA complex, holds a monthly teleconference to discuss issues and monitor sensor development. “We want to leverage the capabilities of our partners,” says engineer Tony Lavietes, who leads the Laboratory’s microsensors program. In addition, an annual workshop is held at Livermore, with more than 100 people from the U.S. and AWE in attendance.

Trebes describes the ideal weapon sensor as a device with zero size and weight. Measuring a few millimeters in diameter and weighing a few milligrams, Livermore sensor designs nearly reach that impossible standard. The biggest obstacle, however, is durability. Industry typically builds sensors to last a few years, but in weapons, sensor lifetimes must be 10 times longer. Once embedded, sensors cannot be easily accessed for



This prototype of a Livermore-designed sensor uses 20 glass fibers, each 300 micrometers in diameter, surrounding a fiber in which laser light illuminates gas contained in a glass capillary. The center fiber is 420 micrometers in diameter.

## Transforming the Nation’s Nuclear Stockpile

When the U.S. stopped nuclear testing in 1992, scientists and engineers at the Department of Energy (DOE) nuclear weapons laboratories embarked on a vigorous effort to acquire the tools for a science- and technology-based stockpile stewardship program. This program includes advanced computing, high-energy-density physics, experimental capabilities, modern diagnostics facilities, and enhanced surveillance techniques. Together, the tools provide the data needed to predict how aging will affect warheads and ensure that the stockpile continues to meet all performance requirements. In this way, components can be replaced before they degrade overall system reliability and safety.

According to Thomas D’Agostino, administrator of the DOE’s National Nuclear Security Administration, “Today’s stockpile remains safe, reliable, and does not require nuclear testing. This assessment is based on a foundation of past nuclear tests, scientific and engineering experiments and analysis including improved warhead surveillance, and the independent judgment of Lawrence Livermore and Los Alamos directors advised by their weapons program staffs.”

Livermore scientists and engineers have long conducted research for assessing the safety, security, and reliability of weapon designs and for annually certifying the nation’s stockpile. In recent years, the emphasis has turned to developing methods to accomplish those activities with a smaller, safer, and more cost-effective nuclear weapons complex. Livermore’s program to design embedded sensors that would promptly indicate problems in warheads is one example of the new focus on transforming the nuclear weapons complex and the stockpile.

Rethinking stockpile stewardship has assumed increased urgency as the number of warheads and bombs shrinks. In 2002, U.S. President George W. Bush and Russian President Vladimir Putin signed the Moscow Treaty on Strategic Offensive Reductions. To comply with this treaty, the U.S. must reduce the number of operationally deployed strategic nuclear warheads to between 1,700 and 2,200 by 2012. In 2004, President Bush issued a directive to cut the entire U.S. nuclear stockpile—both deployed and reserve warheads—in half by 2012. This goal was achieved in 2007, five years ahead of schedule, making the total stockpile almost 50 percent less than it had been in 2001.

President Bush has proposed reducing the stockpile another 15 percent, less than one-quarter its size at the end of the Cold War. To ensure that such a reduced stockpile—the smallest in more than 50 years—would address specific threats, Congress has directed DOE to work with other federal agencies on a comprehensive review of the nation’s nuclear strategy for the 21st century.

repair or replacement. “The supreme challenge is making a sensor remain reliable and robust for 40 years,” says Trebes. “There is no reason to put sensors in warheads if we are not confident they will continue to function for decades.”

An exhaustive qualification process will ensure that sensors can operate in the hostile environments deep within a nuclear warhead. Livermore and AWE researchers are conducting centrifuge tests on some prototypes, and extreme environmental tests, including hydrodynamic experiments at Livermore’s experimental test site, will be scheduled.

Laboratory researchers are also devising methods to extract data from the sensors. One concept is to develop a portable diagnostics unit that will download sensor data and provide the necessary power sources, lasers, and data-acquisition hardware. A military technician would then

attach the diagnostics unit to a deployed warhead, in much the same way that a technician plugs a cable into a port in a car to assess the status of engine components. Separating the embedded sensors from power sources, data-acquisition devices, and lasers ensures optimum safety and reduces the potential for obsolescence.

### Optical Fibers in Sensors

Many sensor designs use glass fibers measuring about 75 micrometers in diameter, smaller than the thickness of human hair. Because they have no electrical requirements, optical sensors are intrinsically safe and are ideal for use in environments that include energetic materials.

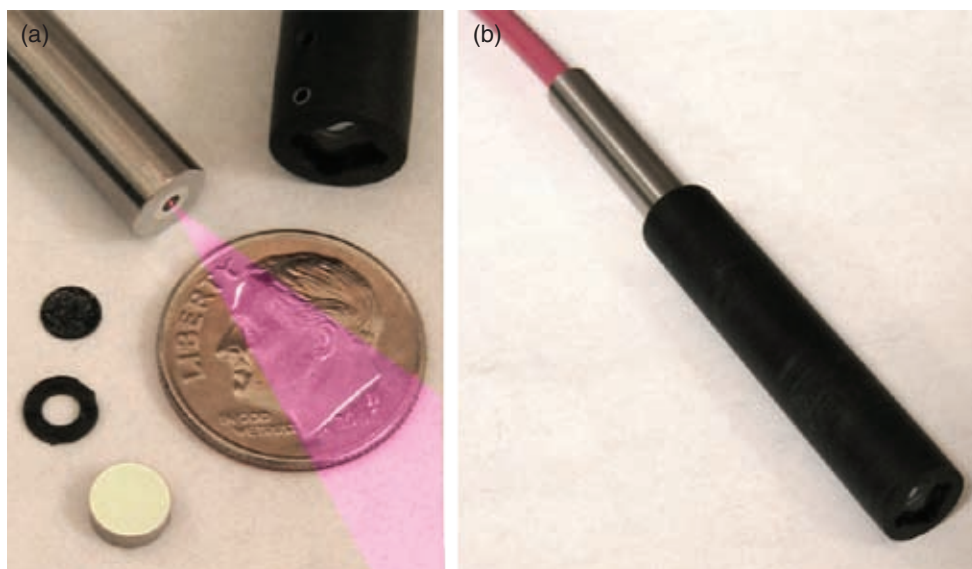
Biophysicist James Chan is working with colleague Chance Carter on a gas sensor that can measure material degradation at a parts-per-million level

of concentration. “We’re developing optical methods to monitor chemical processes that produce any type of outgassing,” says Chan. “If we catch outgassing at an early stage, we can identify which material is decomposing or corroding and mitigate the problem quickly.” The Livermore scientists are collaborating with professors Boris Mizaikoff of the Georgia Institute of Technology and Mike Angel of the University of South Carolina and their graduate students.

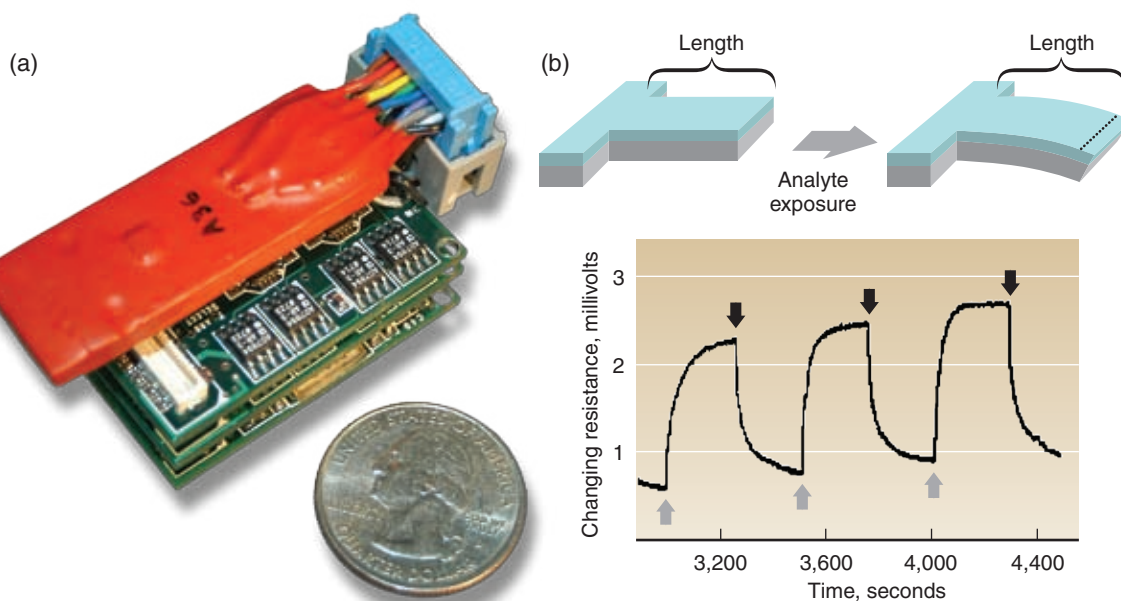
Chan notes that gas sensors are common in manufacturing plants, environmental monitoring systems, and vehicles. Most of these sensors, however, target just one or a few compounds. A major challenge for the Livermore team is to build a sensor that detects a range of volatile compounds.

The team developed prototypes that use Raman and infrared spectroscopy as complementary techniques to identify gases. Both techniques measure the response of molecular bonds to a beam of infrared light generated by a laser and sent through a fiber optic into a hollow fiber waveguide, a small glass capillary with a highly reflective inner metal coating. Infrared spectroscopy measures the amount of light absorbed, which yields a “fingerprint” of the gas. In contrast, Raman spectroscopy records the degree of light scattered by a compound, which also gives a distinct molecular fingerprint. In laboratory tests, the prototypes have accurately detected several common gases. Planned experiments will test for a wider range of gases.

Livermore biophysicist Ward Small is developing another fiber-based gas sensor, in this case to detect and capture hydrogen. This sensor uses a type of getter that is common in industrial applications to remove traces of explosive gases. Hydrogen is both explosive and corrosive, so hydrogen getters are required in environments such as fuel delivery systems.



(a) The components used for Livermore’s getter-based hydrogen sensor include (counterclockwise from top) the sensor case; a fiber bundle, consisting of a central laser delivery fiber surrounded by six light-collection fibers; a getter made of 1,4-bis(phenylethynyl)benzene (DEB) and silicone rubber; a spacer ring; and a mirror. (b) In the assembled prototype, laser light exiting the central fiber passes through the DEB–silicone composite, reflects off the mirror, and makes a second pass through the composite before entering the collection fibers.



(a) One Livermore design uses arrays of microscopic cantilevers to detect a range of gas species. Each green board under the red connector assembly has more than one of these tiny "diving boards," which are coated with polymers a few hundred nanometers thick. (b) As shown in the artist's sketch, the polymer swells as it absorbs gas molecules, bending the microcantilever and changing electrical resistivity (voltage), thereby signaling that gas is present. The graph shows the change in resistance when a gas is introduced three times (gray arrows) and purged (black arrows).

Small is experimenting with an organic getter made of 1,4-bis(phenylethynyl) benzene, or DEB. His design uses photoacoustic Fourier transform infrared (FTIR) spectroscopy to detect changes in the physical properties of the getter, in particular, changes in the optical properties as the getter captures hydrogen. At particular wavelengths, FTIR spectroscopy shows characteristic peaks whose intensities change as DEB bonds with hydrogen atoms.

"The light must interact with the getter at the point where it captures hydrogen to maximize the sensor's sensitivity," says Small. "For example, if the light is confined to the getter surface, the sensor will not respond to changes occurring at a deeper level." FTIR spectroscopy showed that infrared light cannot pass through a getter made of pure DEB. To enable full-thickness light penetration, Small made a 125-micrometer-thick composite of silicone rubber with DEB dispersed throughout. When hydrogen molecules bond to the composite, less light is absorbed. Once embedded in a warhead, the sensor would be fed by infrared laser light supplied through an optical fiber located outside the warhead.

Small, a biomedical optics expert, is also working with light-activated shape memory polymers for treating brain aneurysms. (See *S&TR*, May/June 2008, pp. 4–12.) He notes that the two research areas have similar challenges. Chan is involved in medical research, too. He works part-time at the University of California at Davis developing diagnostic tools that use Raman spectroscopy to detect cancer.

### Microscopic Diving Boards

Another kind of sensor takes a different route to detecting and measuring gas molecules, including volatile organic compounds and water vapor, both of which can indicate degradation of a component. The microelectromechanical systems (MEMS) device uses an array of what biophysicist Tim Ratto describes as microscopic silicon diving boards, each measuring about 120 micrometers long, 50 micrometers wide, and 0.5 micrometers thick.

The diving boards, also called microcantilevers, are coated with polymers a few hundred nanometers thick. The polymer swells as it absorbs gas molecules, in the process bending

the diving board. This bending changes the electrical resistivity of the cantilever, thereby signaling the presence of a gas. By measuring the pattern of deflection across an array of cantilevers, scientists can obtain the chemical signatures for a number of gases. "Our sensor reacts in similar fashion to how odorants bind to different receptors in a mammalian nose," says Ratto.

The sensor is an offshoot of a compact, low-power device that Ratto built with Livermore chemists Brad Hart and Albert Loui to detect vapor from chemical nerve and blister agents such as VX and sulfur mustard. The diving-board sensor will complement others under development, not replace them. To evaluate the design, Ratto has embedded a prototype in a test canister that serves as a simulated weapon. The microcantilever technology should also prove useful in applications such as airport explosives sniffers, food spoilage indicators, and chemical plant monitors.

### Silicon Makes It Work

Livermore mechanical engineer Jack Kotovsky is developing several MEMS-based sensors, which are fabricated from silicon with techniques similar to those



used by the electronics industry. With a background in biomechanics, Kotovsky is expert at designing and building microstructures. His original MEMS contact sensor design was an offshoot of a device he developed for measuring loads on human knees.

MEMS-based sensors are ideal for use in warheads because of their small dimensions, material properties, low power consumption, and mass manufacturability. Embedded sensors must fit into spaces not originally designed to accommodate them. As a result, they must be extremely thin (about one-half the thickness of a human hair) and be able to bend, flex, and stretch to conform to any curved surface. Silicon is used as the sensor substrate because it is inert and deflects and springs back repeatedly to its original shape when pressure is removed. Changes in pressure alter the electrical resistance in silicon. (See *S&TR*, April 2006, pp. 4–9.)

Different MEMS contact sensors are designed to measure forces, pressures, accelerations, and gaps between components. “These sensors will enable us to take measurements that were never before possible,” says Kotovsky. Trebes notes that warheads are sometimes moved. “They are resilient to bumps and shakes,” he says. “However, if they are accidentally bumped, it would be useful to know what stress they received.” A MEMS-based sensor could measure that response.

The first of these sensors will be evaluated on joint test assemblies, weapons without nuclear components, which are used in tests aboard Department of Defense aircraft. Such testing ensures that weapons are compatible with the carriers that transport them. The MEMS sensors will report on the stresses that nonnuclear components experience during flight.

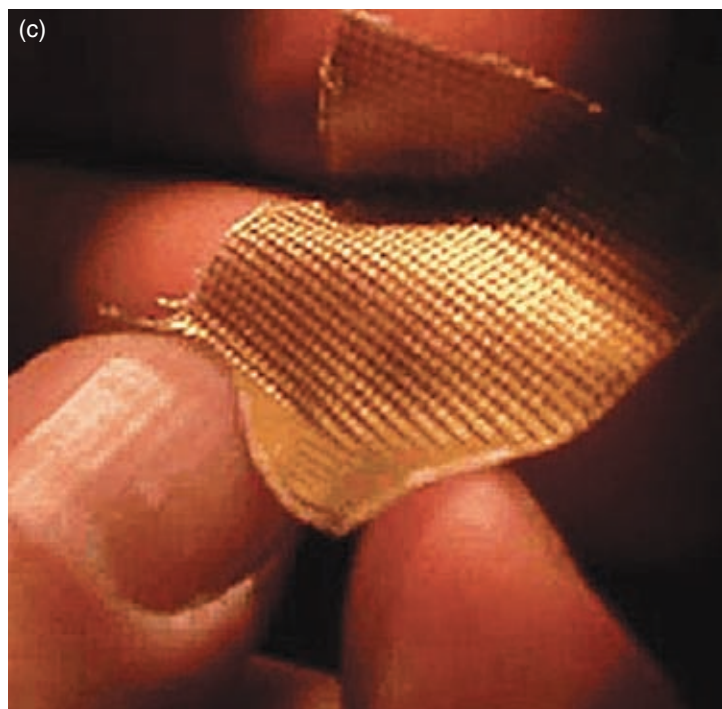
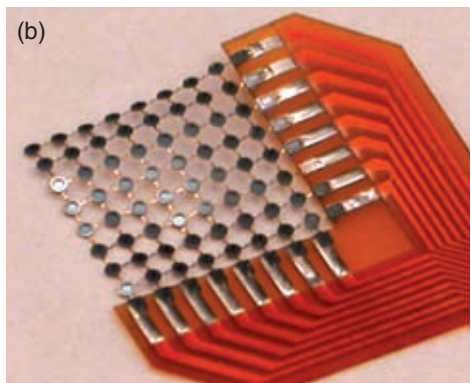
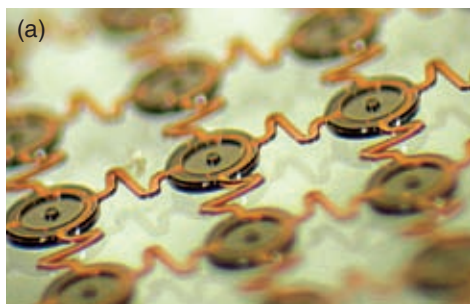
### Sound Waves Tell the Truth

Livermore engineer Dave Chambers is studying acoustic techniques for detecting subtle structural changes in materials, including cracks, pits, voids, gaps, bends, and changes in density and elasticity. Acoustic waves are disturbances in mechanical vibrations in solids, liquids, or gases. Laboratory engineers have used acoustic techniques for years to nondestructively characterize materials. For example, says Chambers, some car mechanics can diagnose problems by listening carefully to the engine.

Chambers studied the response of components with different densities to the entire acoustic spectrum, ranging from human audio frequencies to ultrasound. He chose audio frequencies because these waves propagate through any kind of material.

The acoustic sensors use a fiber Bragg grating—an optical fiber embedded with a repeating pattern that allows only selected

(a) Individual sensors can be combined to form an array.  
(b) One array has 64 units, shown here with electrical leads attached.  
(c) A flexible array of 900 contact stress sensors can conform to any shape.



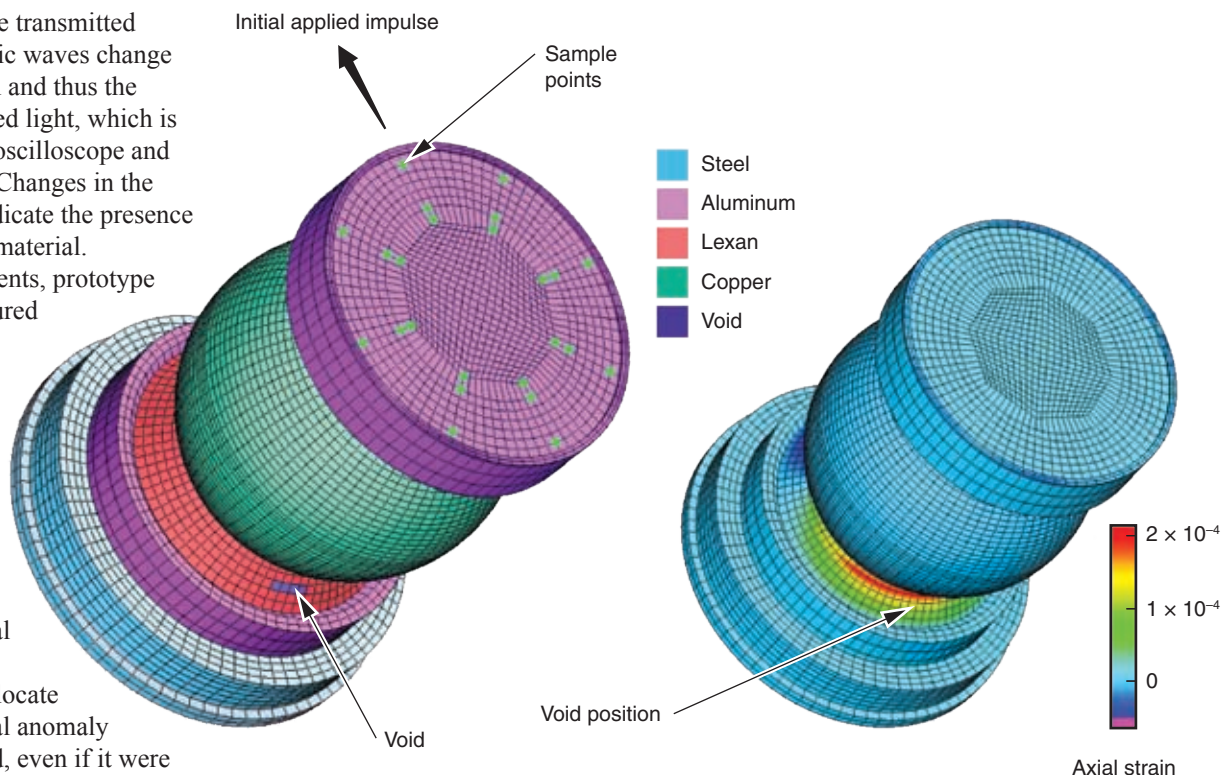
wavelengths of light to be transmitted through the fiber. Acoustic waves change the spacing of the pattern and thus the intensity of the transmitted light, which is recorded by a digitizing oscilloscope and archived on a computer. Changes in the acoustic response can indicate the presence of a crack or void in the material.

In laboratory experiments, prototype fiber-optic sensors measured the acoustic response at different points on a sample structure. Chambers is also using computer simulations to determine what engineers could learn from measurements supplied by a network of acoustic sensors. Initial results show that such a network could precisely locate the source of a vibrational anomaly caused by a crack or void, even if it were located deep within a part or assembly.

"Sometimes we only need to localize the problem," says Chambers. "The designer may be able to diagnose the problem just from knowing its location, especially if acoustic data are supplemented with measurements from another kind of sensor." Current simulations are modeling more complicated component geometries.

### Leaving behind the Cold War

As costs continue to rise for maintaining the aging stockpile, a network of embedded sensors monitoring some or all of the nation's warheads seems to many experts a smart way to leave the Cold War legacy behind and introduce a new era of stockpile stewardship. Embedded sensors



In computer simulations of a hypothetical component made from different materials (left), a network of 18 acoustic sensors precisely locates the source of a flaw (void). Simulation results (right) indicate that axial strain increases near the void and potentially weakens the component.

would reduce or eliminate the transport and dismantlement of weapons, increase reliability, and enhance confidence in the enduring stockpile.

No one sensor is a complete solution by itself. But together, networks of embedded sensors could provide valuable information about the stockpile much earlier and at much less cost. In so doing, say Livermore weapons experts, the weapons complex and the stockpile would be well on the road to transformation.

—Arnie Heller

**Key Words:** embedded sensors, Fourier transform infrared (FTIR) spectroscopy, hydrogen getter, joint test assemblies, microelectromechanical systems (MEMS), Moscow Treaty on Strategic Offensive Reductions, nuclear stockpile, Raman spectroscopy, stockpile stewardship.

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